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17JUL02 E733844-1 C87283
P01/7700 0.00-0216544.7

2. 0216544.7 — 17 JUL 2002

3. Full name, address and postcode of the or of each applicant *(underline all surnames)*

PROFESSOR NOEL A. WARNER
40 HIGH HOUSE DRIVE
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BIRMINGHAM B45 8ET

Patents ADP number *(if you know it)* — 12323001

If the applicant is a corporate body, give the country/state of its incorporation

4. Title of the invention

DIRECT COAL-BASED CONTINUOUS STEELMAKING

5. Name of your agent *(if you have one)*

"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*

Patents ADP number *(if you know it)*

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and *(if you know it)* the or each application number

Country	Priority application number *(if you know it)*	Date of filing *(day / month / year)*

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Number of earlier application	Date of filing *(day / month / year)*

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Claim(s)	CF
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Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. I/~~We~~ request the grant of a patent on the basis of this application.

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DIRECT COAL-BASED CONTINUOUS STEELMAKING

This invention relates to the production of molten steel of closely controlled composition directly from iron ore fines, non-coking coal and flux material. More particularly, the present invention is concerned with providing a practical means for establishing, maintaining in stable operation, taking-off-line for maintenance or planned shut-downs and re-starting a process employing a number of melt circulation loops arranged in series to effect integrated ironmaking and steelmaking on a truly continuous basis.

EP 0266975 and US Patent 4701217 disclosed the use of a stationary or slowly moving protective molten layer below the relatively fast moving layer of carrier material to reduce the erosion of the hearth or floor of the furnace in which smelting reduction is taking place in a melt circulation loop. This method is satisfactory for the examples cited in which a molten matte phase is the carrier material and the protective layer can then be a denser metallic alloy, but use of molten lead in steelmaking or refined ferroalloy production introduces environmental and health and safety issues, which are better avoided if at all possible.

There is a well known technique for melting and refining titanium and other reactive metals referred to as cold hearth refining. Cold hearth refining is named as such because of the use of a water-cooled copper hearth, which solidified molten titanium in contact with it and forms a skull of the material being melted. The molten titanium being refined then flows across the solidified skull, which becomes the conduit. At first sight, experts would dismiss this approach for iron and steelmaking on the grounds of energy losses involved in very large scale processing would make this approach hopelessly uneconomic. However, if the cold hearth were not actually cold but at a temperature of say 800°C or even hotter and the concept was developed for a generation of high pressure steam under benign conditions for advanced power generation from readily available coal resources and preferably with virtually zero gas emission after carbon dioxide sequestration, then detailed assessment yields a totally different answer and could provide the key to continuous steelmaking for the future.

Increased electrical demand must flow from the introduction of zero emission technology and in the present case the need for air separation and CO_2 sequestration sometime in the future is readily apparent. If it is accepted that plant electrical requirements using coal and generated in-house using near to zero gas emissions may be superior to buying in electricity or at least competitive in the broader sense, when taking into account the whole production process, then it is immaterial how the steam is raised for power generation provided it is safe, reliable and cost-effective.

Direct radiation from the external surfaces of the various frozen walls and hearths is potentially as good as any other way to generate high pressure steam. Staged oxygen combustion throughout the entire melt circulation circuit of the gases from the charge arm of the ironmaking loop in association with melt

circulation and controlled extraction of heat from walls and hearths, whilst transferring heat to the top hearth and melt surfaces by radiation and top blowing/direct flame impingement, has in effect provided a large surface area ideally suited to radiative heat transfer to boiler tubes under benign conditions. The intensity of heat release is compatible with the requirements for supercritical steam raising, including those required for the EC Thermie Programme, where efficiencies in excess of 50 pct are projected. However, for the present purposes sub-critical steam may be preferred, even though preliminary calculations indicate the system is ideally suited to supercritical conditions.

Returning to the frozen shells themselves, the key issue is to identify the most effective way of holistically conducting both steelmaking and power generation together. Provided the overall energy balance permits diversion of heat to frozen shells as proposed, there would seem to be no rational impediment to its implementation. There is, of course, a limit to the amount of heat which is available for this purpose and it can be shown that the maximum rate of heat flow permissible for say a 500,000 tpa virgin steel plant employing melt circulation would be somewhere in the region of 30-40 MW. A viable means by which frozen shells can be adopted throughout the entire circuit, while keeping below the level specified above, has been identified. The major assumptions made and the various considerations are summarized in what follows.

(1) The convective heat flux from the bulk of the liquid metal to the solid lining is determined by the product of the heat transfer coefficient and the temperature driving force.

(2) The melt circulation rate is very large in comparison with the steel production rate, so the carbon concentration in a particular loop is virtually constant.

(3) If the temperature of a thermal sink adjacent to the cooler side of the freeze lining is fixed, as for example by having steam tubes undergoing boiling imbedded in the sink, then in response to changes in heat flux both the thickness of the freeze lining and the temperature of the cooler side will adapt to establish or restore steady state conditions.

(4) Solid-liquid transformation processes in either direction on the hotter side of the lining will take place heterogeneously only on the face of the freeze lining rather than in the bulk of the liquid metal. This assumes that supersaturation levels are not excessive, or in other words thermal changes or concentration levels do not alter very abruptly.

(5) At the elevated temperatures involved solid-liquid transformation take place rapidly and equilibrium is established at the solid/liquid interface, or in phase diagram terms for a given temperature these are the solidus and liquidus compositions.

(6) To avoid nucleation and growth of solid phases within the bulk of the liquid metal, the lowest temperature in a particular loop is limited to the liquidus temperature.

(7) The highest temperature required in the circulating liquid metal in a particular loop is a function of how much each has to be transported by the liquid between arms of the loop and also the amount of heat to be transferred by flame impingement and other mechanisms.

With improvement in refractories, the erosion of the furnace hearths for melt circulation processes involving ferrous metals can be contained, but clearly it would be better to eliminate the potential problem by a totally new approach. Although not immediately obvious, the melt containment problem is aggravated for the larger scale operations such as direct continuous steelmaking, where process engineering calculations indicate the need for reactors of swimming pool size as opposed to the relatively smaller horizontal or vertical vessels used in other bath smelting processes. Whilst replacement of refactory linings at the sides of such furnaces is possible without closing down the plant, it is difficult if not impossible to replace the refactory of the hearths. With "swimming pool" reactors the other issue of concern is what to do with the metal contents of a pool if a hearth repair or replacement is needed. A related but still important issue is an effective way of bringing a swimming pool reactor back on-line after repair and, indeed, the problem of start-up in the first instance. All these issues may be disadvantageous to the widespread use of melt circulation technology in practice.

It is therefore an object of the present invention to obviate or mitigate such disadvantages.

The process is designed to take place in three melt circulation loops each comprised of two parallel "swimming pool reactors". There are no connections to the hearths or walls of these swimming pool reactors, but rather all access is from above whether that be gas-lift snorkels, melt siphons or top blow lances. This approach facilitates the establishment of pools of molten metal totally contained by a solidified shell of material of similar composition and completely eliminates concerns about hearth erosion and slag/metal attack on refactories. The external surfaces of the solidified iron shell may optionally be clad with heat resistant alloy to protect against oxidation and scaling as well as providing mechanical strength and dimensional stability.

During start-up, temporary shutdowns or planned prolonged periods off-line, the various pool ancillaries are raised and kept in the up position to enable a low voltage, heavy current mains frequency three-phase AC electric circuit to be established using transformed mains electrical supply for direct resistance or "so-called" conductive heating. The provision of three independent melt circulation loops permits phase balancing of the mains power supply without undue complexity or expense. In normal operation the solidified shell is maintained at its steady state thicknesses by radiation to steam boiler tubes associated with an advanced reheat steam turbine for power generation. This will provide all the electricity needed

both for air separation and carbon dioxide liquefaction prior to its sequestration in accordance with a near to zero gas emission operating philosophy without external input.

If heat is extracted from the walls and base of a very large solid slab of iron while a heavy alternating current is passed from one end to the other, in due course a liquid pool will be formed, which can be maintained as such under melt circulation conditions by controlling the current input. Similarly, the provision of heat to the top surface of either side of a melt circulation loop by post-combustion radiant heat transfer, by direct flame impingement, or top blowing at the same time as heat is being extracted both to satisfy process requirements and through the base and walls to an external sink, the molten pool can be maintained under melt circulation conditions after the current flow has been switched off. This is the rationale behind the design of the swimming pool reactor system and is the basis of the assertion that slag/metal attack and hearth erosion will be completely eliminated by this novel approach.

However, for those hearths in which the oxygen potential of the gas is higher than that for metallic iron stability, steps clearly have to be taken to protect the exposed surfaces of solid iron from oxidation. A system has been devised to accomplish this by shielding the exposed areas and purging the immediate surrounds with gas not oxidizing to iron. Nitrogen or argon cannot be used for this purpose, because their presence in the process off-gas would complicate CO_2 separation and its ultimate disposal. It is estimated that some 20-25 pct of reducing gas produced in the ironmaking loop will be needed for this purpose, bearing in mind that at least three of the six hearths will have gas atmospheres already not oxidizing to iron. All this purge gas ends up in the principal gas flow to be finally combusted in the post combustion (PC) arm of the ironmaking loop so there are no losses as such.

Without taking positive steps there could still be a potential problem with sulphidation of exposed solid iron surfaces at high temperature. Exposed areas in both the ironmaking arm and the metallised raft melting arm will require shielding and purging with low sulphur gas because the raw gas in both of these will contain enough sulphur to cause problems, if appropriate steps were not taken.

An embodiment of the present invention will now be described, by way of example, with reference to the accompanying drawings, in which:-

Fig. 1 is a schematic sectional plan view, which removes details of gas ducting and the like from view, of a coal-based continuous steelmaking plant for virgin ore as the sole source of iron units, in which the method of the present invention can be performed.

Fig. 2 is a schematic general arrangement in sectional plan of three melt circulation loops connected electrically to form a balanced circuit for a three-phase alternating current power supply when all pools are totally solidified as after a prolonged stoppage or as for initial start-up.

Fig. 3 is a schematic half sectional elevation view across the width of one of the "swimming pool" reactors, showing the solid shell of iron for containment of the circulating molten iron, the means for protecting exposed solid iron surfaces from oxidation or sulphidation, the general configuration of the steam boiler tubes for power generation, the arrangements for sealing the liftable top enclosure, the method for accommodating thermal expansion of the solid shell and the general features of the basal assembly.

Referring now to Fig. 1, three melt circulation loops A, B and C are formed by interconnecting pools of molten iron 1, 2, 3, 4, 5 and 6 containing decreased levels of carbon concentration in the order A, B, C. Molten iron is the direct product of smelting reduction of iron oxide ore and which therefore contains minor amounts of the usual incidental impurities C, Si, Mn, SP and during the process of steelmaking these impurities are refined down to low levels to comply with specification limits to form steel. Hereinafter, the liquid metal in each of the three loops will be referred to simply as molten iron. Because the molten iron circulation rate within each loop vastly exceeds the rate at which metal is actually produced from the composite charge 7, the melt composition can be considered uniform throughout each loop and therefore equal to that of the metal overflown or otherwise extracted from each loop sequentially from B to C via 9 and finally from C via 18 to supply, for example, a continuous casting machine or optionally, further continuous refining to ultra-low carbon steel (ULC) in a tower refiner (not shown). A channel or ramp 8 interconnects loops A and B across which the metallised raft produced in 1 is propelled or projected onto the surface of 3 in the first of the steelmaking loops B.

For given melt circulation rates in the various loops, the molten iron composition and temperatures in each loop are determined by the physical dimensions of the pools 1, 2, 3, 4, 5 and 6, the amount and composition of solid feed material introduced at 7, the rate of oxygen addition and where in the overall circuit it is added and in what proportion it is relative to the gas flow rate at the particular point of addition. A major influence is also exerted by the molten iron circulation rates in each of the loops, A the ironmaking loop, B the primary steelmaking loop and C the secondary steelmaking loop. The circulation rate of molten iron in each of these loops is distinctly different and is controlled by the rate at which an inert gas is injected into the upleg snorkels 10, 11 and 12 of the gas-lift pumps (RH-type) as used in steel vacuum degassing worldwide, which extend into the molten iron at the left-hand ends as viewed in Fig. 1 of pools 2, 4 and 6. The downleg snorkels 12, 13 and 14 extend down to into the molten in pools 1, 3 and 5. At the opposite end of all pools, siphons 15, 16 and 17 of similar design to the gas-lift pumps are extended down into the molten iron to interconnect pool 1 to pool 2, pool 3 to pool 4 and pool 5 to pool 6. All the snorkels in the gas-lift pumps and the siphons are joined immediately above to bodies in which a reduced pressure is maintained to effect forced circulation of molten iron in a closed loop path.

The gas-lift pump and siphon devices can be lifted out of the molten iron to leave rectangular pools of molten iron of the size and shape of swimming pools and these may accordingly be referred to as swimming pool reactors.

Heat can be extracted directly by thermal radiation from the walls and bases of the swimming pool reactors for the purpose of generation high pressure steam under benign conditions to facilitate the generation of electricity, employing either supercritical or subcritical steam conditions and an advanced reheat steam turbine cycle. Under steady operating conditions, the solidified shells in various parts of the overall circuit can be maintained at a pre-determined thickness by controlling the same variables as already referred to as determining melt composition and temperatures in the three loops, coupled with manipulation of steam raising conditions external to the frozen shells.

At the discretion of the process operator, the plant can be closed down by discontinuing feed to the ironmaking loop, turning off the oxygen and inert gas supplies and then raising the snorkels out of the pools. At this juncture the circuit consists of six rectangular pools of molten iron devoid of any ancillaries. Without the provision of heat input, the molten iron would begin freezing onto the solid iron shells and eventually six frozen solid pools, rather like skating rinks, would be all that remained. Before this happens, if the process is to be restarted after a temporary shutdown, it is desirable to maintain the steady-state shell thicknesses at their former levels. This can be achieved electrically by making use of the so-called skin effect, in which for large-size conductors supplied with alternating current at mains frequency, the current penetrates to a very limited extent and is confined to the skin on the outside. Accordingly, direct resistance or so-called conductive heating is the appropriate means to provide the heating required.

Referring now to Fig. 2, three-phase mains frequency electricity is reduced in voltage from transmission voltage to plant requirements by an appropriate step-down transformer station for the steelmaking plant. Depending on how the various pools are connected together, the voltages required to maintain the steady-state frozen shells depend on the electrical characteristics of the whole circuit, which includes the shells themselves and water-cooled bus system interconnecting the individual pools, which constitute the electrical load. In Fig. 3, 19 represents the regulated low voltage input supply to a circuit comprised of the six pools interconnected to each other to provide three equal loads. For the example shown, this is achieved by connecting 1 with 3, 2 with 5 and 4 with 6 to effect what is known as a star circuit. For this, if the loads are equally balanced there is no need for a fourth conductor, because there would be no net current flow in the neutrals, N, and the neutrals would be earthed. However, it is recognised that a four-wire system may be needed, if the loads are not identical. The alternative method of connecting the three electrical loads is a so-called delta circuit, which will not be shown as this is well known those skilled in the art.

As an indication of the voltages and currents involved in a real situation, the resistivity of Fe-C is about $1.39 \times 10^{-6}\Omega$ m and the skin depth at the melting point for 50 Hz is about 80 mm. For two nominal pools, each 6 m in overall width by 60 m in overall length, both connected in series the effective resistance is about $1.23 \times 10^{-4}\Omega$. Based on resistance only for a power input of say 13.3 MW per phase, a potential

difference of about 40 V would be required across the load and the current flow would be 330 kA. Voltages of this magnitude are normally considered low risk in terms of the electrocution, but clearly the relevant electrical code would have to be complied with. For the star connection shown in Fig. 2, this corresponds to a line voltage of 70 V to provide a total power input of about 40 MW to the six pools at a mean heat flux at the solid/liquid metal interface of 0.0136 MW/m^2. The voltages quoted above are indicative only, because they ignore mutual inductance. voltage drops in the water-cooled bus system and other electrical effects but are suitable for an initial appraisal of system feasibility.

Referring now to Fig. 3, the liquid metal pool 19 is non-specific but is representative of pools 1, 2, 3, 4, 5 and 6. The solid iron shell established under steady operating conditions is shown as 20. A purge gas header 21 supplies ultra-low sulphur/non-oxidising to iron gas to a pipe 22, one of a number of such pipes attached to the header at various points along the length of the pool. This purge gas on being admitted to the gas-tight enclosure, comprised of top-hat enclosure, 23 and basal enclosure 24, provides an inert gas atmosphere throughout the whole volume of the enclosure except for that containing reactive gas in the gas phase 25 above the molten iron. Accordingly, protection is provided to the outer surfaces of the solid shell, the steam boiler tubes 26 and ancillaries such as the heat resisting alloy components 27, which provide skid mounting at the base of the solid shell, and the sideways movement trolley 28 extending the length of the pool, which is actuated so that it moves backwards and forwards as the solid shell expands or contracts in width. The latter features are to combat stresses from thermal expansion and are designed to allow freedom of movement of the solid shell, particularly when totally solid at start-up or after prolonged shut-down. Both the skids and the trolley system are used in conjunction with heat resistant alloy plates to control creep and distortion of the solid shell during prolonged operation at elevated temperature.

The top-hot enclosure is provided with a skirt 29, which is immersed in a channel 30 containing fusible alloy such as lead-bismuth eutectic, which forms a continuous seal around the perimeter. The channel or trough containing the fusible alloy is attached to the basal enclosure and is heated at all times by electrical conductive heating so that the top-hat enclosure is free to thermally expand or contract, whilst always maintaining a leak-proof gas seal.

Inside the top-hat enclosure a composite lining of low-thermal mass insulating materials provides lightweight insulation and permits rapid heating after shut-down without fear refractory damage. On the highest temperature faces, high purity alumina fibrous board currently commercially available or microporous materials currently under development are used.

The purge gas enters the gas space above the molten iron through a small clearance passageway 31, bounded by the top surface of the solid shell on one side and on the other by several layers of ceramic fibre board 32 or comparable material, which is profiled to deliver a shroud of protective gas to the solid iron areas vulnerable to oxidation and possible sulphidation immediately above the molten metal surface. To achieve this, the boards project a short distance into the reactive gas space 25, as shown schematically at

33. The purge gas velocity is controlled by varying the pressure upstream to the header 21 to preclude back diffusion of reactive gases to the exposed high temperature surfaces of solid iron.

Although not shown in Fig 3, it will be necessary to control induced current effects in loops completely surrounding the heavy current-carrying solid shell and its molten iron contents. Those skilled in the art will recognise the need for this and will devise ways and means for breaking such circuits by electrically insulating such metallic loops so that induced currents are minimised or preferably completely eliminated.

For routine inspection or maintenance, means for lifting the top-hat enclosure, which is effectively a moveable lid on the "swimming pool" reactor, must be included. The arrows shown as 34 and 35 signify such an arrangement, where the options include hydraulic hoists and gantry craneage. Because of the use of lightweight insulating materials without conventional refractory arches and brickwork, the lifting requirements for handling a one-piece fabricated top-hat enclosure for say a 60 m length "swimming pool" reactor is not excessive and well within the bounds of commercial practice, particularly that associated with dry docking of ships and bulk loading of whole barge cargoes. Although not absolutely essential, it would be convenient to provide clear areas adjacent to the "swimming pools" so that individual top-hat enclosures can be parked nearby.

The fabricated steel basal enclosure 24 encases a refractory concrete or firebrick base 36 and structural steel members 37, which are the principal load bearing members for the whole "swimming pool" reactor. The structural supports are ventilated, possibly forcibly, to ensure the reinforced concrete floor 38 is not over-heated and not over-loaded. Because the solid shells are typically around 1 m in thickness, it is highly unlikely that a break-out of liquid metal should occur, but in the event, the large thermal mass of the firebrick lining can be regarded as a safety lining.

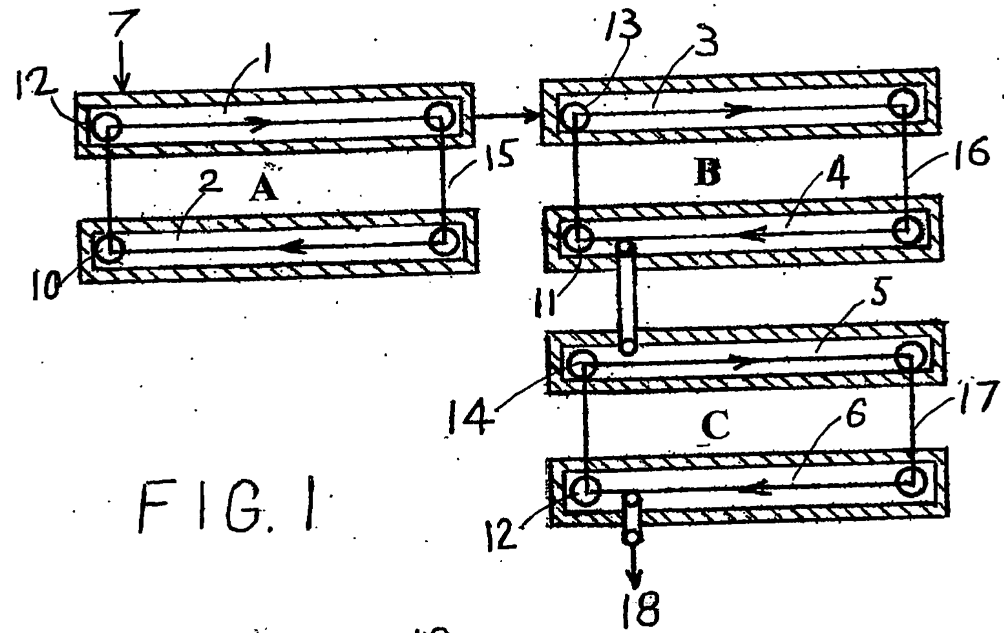


FIG. 1

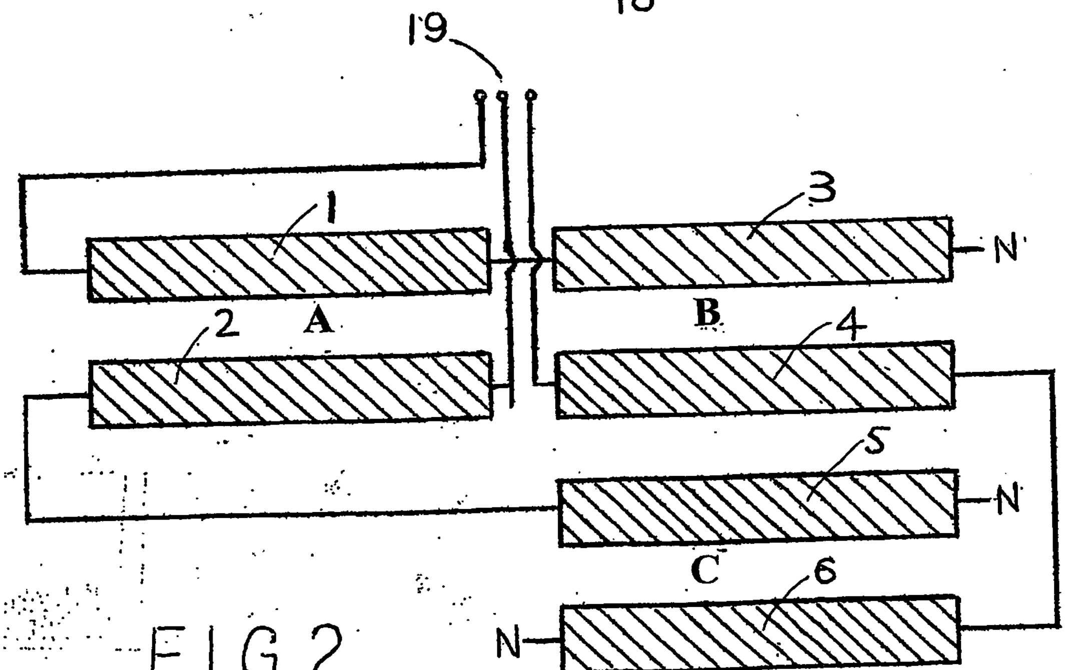
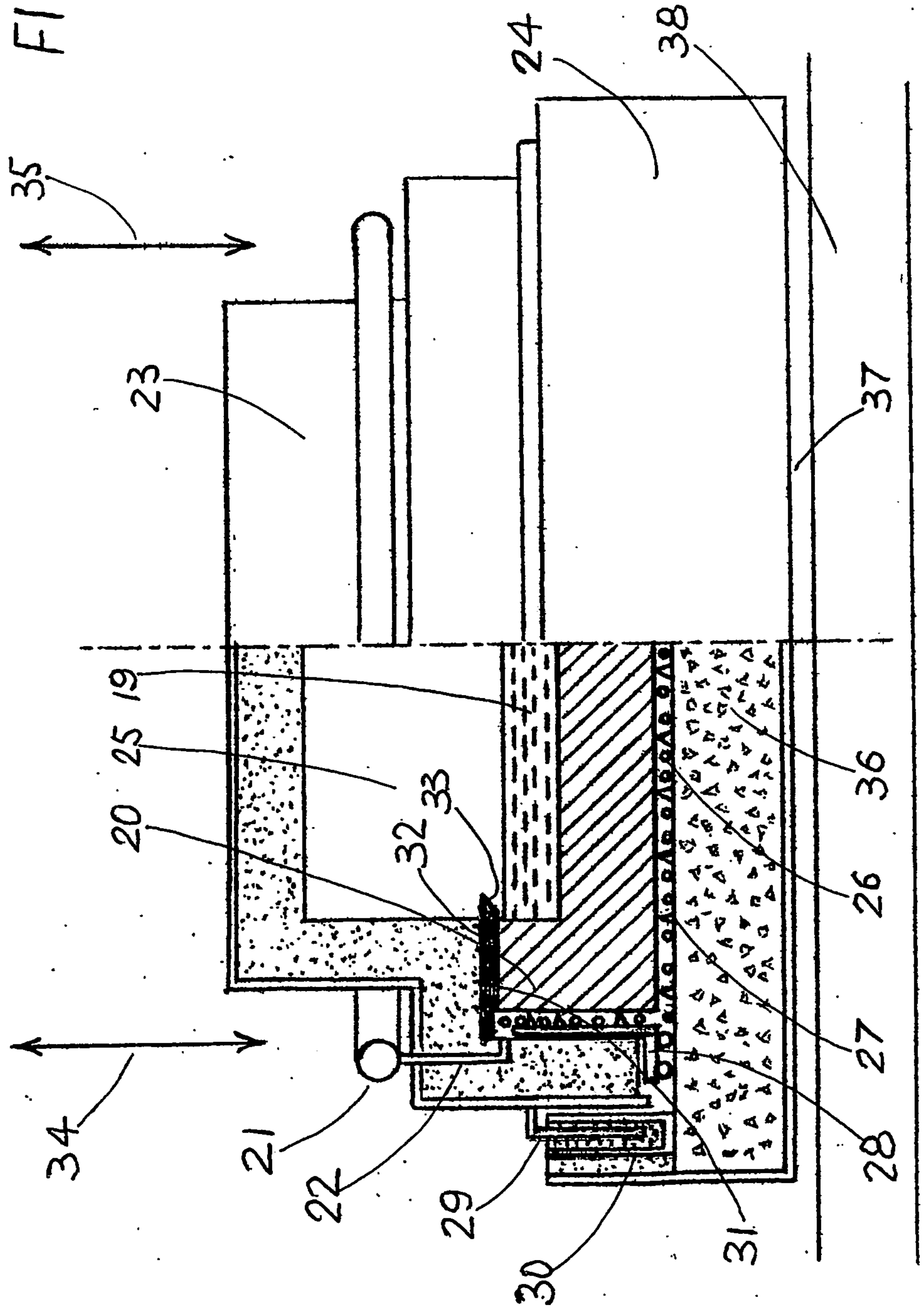


FIG. 2

2/2

FIG. 3



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